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A CRITICAL REVIEW OF NOTCH SENSITIVITY IN

STRESS-RUPTURE TESTS

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SUMMARY

The English and German literature on notch stress-rupture test-ing was reviewed and information obtained on: (1) the effect of notching on the rupture strength in general and, in particular, the influence of the unnotch ductility on the notch sensitivity; (2) the effect of chemical composition and heat treatment on the notch stress-rupture characteristics of low-alloy heat-resisting steels; (3) the mechanism of stress-rupture embrittlement and notch sensitivity in these low-alloy steels; and (4) a comparison of the influence of notch geometry on the notch strength in stress-rupture tests and in conventional tensile tests.

In a stress-rupture test, the strength at a given time for a notched specimen may be either greater or smaller than the corres-ponding strength of an unnotched bar. Whether the strengthening or weakening effect predominated appeared to be related to the unnotched ductility. For the alloys considered, the notch strength was greater than the unnotch strength when the ductility exceeded approximately 10 percent. Below an unnotch ductility of approximately 5 percent, the strength of the notched bar fell below that of the unnotched specimen and the trend of notch rupture strength with time closely paralleled that of the unnotch ductility.

Low-alloy Cr-Mo steels containing from 0.9 to 1.5 percent nickel were extremely notch sensitive in rupture tests at 932° F (500° C) when either quenched and tempered or normalized and stress relieved. Elimination of the nickel appeared to reduce the notch sensitivity greatly. Annealing or sphereodizing Cr-Ni-Mo steels greatly reduced the strength at short times to rupture. Such structures, however, are not notch sensitive and when compared with the normalized or the quenched-and-tempered steels may possess superior notch rupture strength at very long times to rupture.

An analysis of the data for notch rupture tests on low-alloy steels indicated that a precipitation reaction may be responsible for the rupture embrittlement and consequent notch sensitivity of the Cr-Ni-Mo steels.

For the alloys considered, the general influence of notch sharpness on the notch rupture strength at a particular time to fracture was the same as the effect of this variable on the room-temperature notch tensile strength.

INTRODUCTION

It is well known that under static service conditions certain alloys may be severely embrittled by the presence of stress raisers or "notches" such as are associated with threads, holes, shoulders, splines, and so forth. This embrittlement results in service failures at much lower loads than would be predicted from the conventional tensile or yield strengths without consideration of the notch effect. Because stress raisers are nearly always present in any machine part, the evaluation of the behavior of metals under their influence is a very important design problem.

When the tensile ductility falls below a few percent, the material nearly always is weakened by a severe stress concentration. The converse of this statement, however, is not necessarily true and some alloys even though exhibiting high tensile ductilities are still extremely sensitive to stress concentrations (references 1 and 2). The factors that govern the notch sensitivity of a metal are thus incompletely understood.

Notched-bar tests are therefore increasingly used to evaluate directly the response of an alloy to a severe stress concentration. The oldest of these tests applied is probably the impact bending test. More recent investigations (reference 2) show that tests of a cylindrical tensile bar containing a sharp circumferential V notch evaluate the brittleness of high-strength low-alloy steels in the same manner as the impact test, and subsequently static notch tests have been substituted extensively for the impact test in the evaluation of ship steels. Such experiments yield more reproducible and more easily interpreted results than the more complicated and less carefully controlled impact test.

Inasmuch as notches have been shown to have a pronounced effect on the behavior of some metals at room and low temperature, it is important to investigate the effect of notches on high-temperature behavior, particularly under the conditions of long-time loading.

This problem has been recognized in Germany and Switzerland. Some subsequently discussed, experimental work along these lines has been carried out in European laboratories primarily on heat-resisting low- and medium-alloy steels that were used during World War II in

many applications where stainless steels would normally be applied
in the United States. In addition, the results of a few tests have
been reported for high-temperature alloys of the present-day type.
To date in this country, practically no notch-rupture data have been
published except for lead alloys used in cable sheaths.

Apparently, no critical correlation of these data has been as
yet attempted. A few investigators (references 3 and 4) have recog-
nized the importance of rupture ductility in determining the response
of a metal to notching in a rupture test. In many investigations,
however, the ductilities of rupture specimens are not reported,
perhaps because the influence of this variable on the conventional
(unnotch) rupture strength seems to be rather small (reference 5).

In the following discussion prepared at the NACA Lewis laboratory
previously reported data on notch-rupture testing is reviewed and an
attempt made to:

(1) Determine the influence of notches on the rupture strength
of all materials for which data are available

(2) Determine the effect of chemical composition and heat treat-
ment on the notch rupture strength of certain low-alloy
heat-resisting steels

(3) Analyze the published data to reveal the mechanism of stress-
rupture embrittlement in low-alloy steels

(4) Compare the influence of notch geometry on the notch strength
in stress-rupture tests with its influence in conventional
tensile tests

A considerable scatter, which is particularly pronounced for the
low-alloy heat-resisting steels, is encountered in most of the data
reported. This scatter is explained in part by the fact that it was
not always possible to test samples from the same heat of metal. In
most cases, however, the embrittling effects well exceeded the
scatter of the data, and definite conclusions are possible.

METHOD OF DATA PRESENTATION

The rupture data have been replotted on a semilog rather than
log-log scale because:

(1) Differences of properties between specimens of different
geometry if rather small are revealed more clearly on a linear
ordinate scale

(2) On the basis of theoretical considerations, it has been
shown that the semilog representation has a fundamental significance
(reference 6)

Stresses (strengths) shown are the conventional values based on
the load divided by the initial area at the minimum section. The
reduction of this area at fracture is referred to as "ductility;"
ductility and elongation are given in percentages. Conventional
short-time tensile test data are plotted at 0.1 hour. Where available,
information is given on the figures regarding the exact specimen
shape, the heat treatment, and the chemical composition.

A given notch geometry (fig. 1) may be sufficiently defined by
the following quantities: (1) depth, expressed in percentage of
cross-sectional area removed by the notch, namely $\left[(d_1{}^2-d_0{}^2)/d_1{}^2\right]100;$
(2) sharpness, which is the ratio between one-half the diameter at
the minimum section and the radius at the notch bottom, namely,
$d_0/2R;$ and (3) the flank angle θ, which is the angle between corres-
ponding elements of the conical surfaces forming the notch. An alloy
is herein referred to as "notch sensitive" if the ratio between the
notch-rupture strength and the conventional (unnotch) rupture strength,
referred to as the "notch strength ratio" is less than unity.

RESULTS AND DISCUSSSION

Effect of Notches on Rupture Strength and
Influence of Ductility

Notch rupture- and unnotch rupture-strength data for several low-
alloy bolting and boiler steels are shown in figures 2 to 6. Also
shown are the elongation and ductility at fracture. All these tests
were carried out at 932° F (500° C) and in most cases covered time
periods well over 10,000 hours. As shown in the figures, two types
of notched specimen were employed: (1) a bar of circular cross
section containing two circumferential 90° notches having a notch
radius of 0.002 inch and a notch depth of 23 percent; and (2) bars
containing notches having notch radii of 0.20 inch but with variable
depth. For tests on these bars, the load applied was constant and
the stress was varied by varying the notch diameter and the cylindrical
diameter with a resultant variation in notch depth of from 25 to 44
percent.

In all cases, the notch stress-rupture strength at short times to
rupture exceeds the strength for an unnotched bar by an amount which
depends primarily on the depth of the notch. With increase in rupture
time two distinct classes of behavior are observed:

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(1) The strength of the notched bar remains above that of the unnotched specimen as is characteristic for ferritic stainless steels (reference 7) of the type shown in figure 2 or may gradually approach and eventually equal the unnotch strength. The latter behavior is typified by the Cr-Mo steels (references 7 to 9) shown in figures 3 and 4 and also by a variety of nickel-free annealed boiler steels discussed in reference 9.

(2) The strength of the notched bar decreases rapidly with increasing time to rupture and falls well below the strength of the unnotched specimen. This notch-sensitive behavior is typical for Cr-Mo-Ni steels (references 7, 8, and 10) and is shown for the quenched-and-tempered structure of two steels of this type in figures 5 and 6. If the tests extend to very long periods of time, over 30,000 hours, the notch strength (fig. 6) may "recover" and become equal to or possibly greater than the strength of the unnotched bar.

It appears that these two observed classes of strength behavior are related to the unnotch ductility. If the unnotch ductility remains above approximately 10 percent (figs. 2 to 4), the notch strength is equal to or greater than the unnotch strength. For the Cr-Mo-Ni steels (figs. 5 and 6), the ductilities fall very rapidly in a restricted range of rupture times to values less than 2 percent and the strength of the unnotched specimen falls below that of the notched bar. The trend in notch strength then very closely parallels that of the unnotch ductility even to exhibiting the recovery at long times to rupture (see fig. 6).

The previously discussed data for low-alloy steels constitute the only published notch stress-rupture results which clearly reveal the influence of unnotch ductility. A few data have been reported, however, for lead cable sheathing (reference 11), which further support the important influence of ductility in determining the notch sensitivity.

Results of notch and unnotch rupture tests for two lead cable sheathings are shown in figure 7. Tests were made on bars of rectangular cross section with 60° sharp (notch radius, 0.005 in.) V notches cut in the width direction. Unfortunately, the only elongation values for these sheaths were at room temperature; however, they have been included for purposes of comparison in figure 7(b). According to the data presented in reference 11, it would be expected that the general effect of an increase in temperature is to reduce the elongation. The notch rupture strength (fig. 7(a)) of the calcium lead is approximately 20 percent below the strength values for the unnotched bars over the entire range of rupture times investigated.

Conversely, the chemical lead is strengthened by notching over approximately the same range of times to rupture. An examination of the corresponding elongations confirms the previous conclusion that for a material having high unnotch ductility, namely, chemical lead, the notched specimen is stronger than the unnotched bar. On the other hand, for the material of low unnotch ductility, namely, calcium lead, the notched specimen is weaker than the unnotched bar.

A few notch tests have been made (reference 3) on several alloys corresponding to British and American turbine materials. It is reported that a 60° V notch with a 0.02-inch radius removing 50 percent of the cross-sectional area reduces by 20 percent the 35-hour rupture strength of a Ni-Cr-Co alloy (composition: 0.47 C, 14 Cr, 14 Ni, 10 Co, 1.4 Si, 1 Mn, 3 W, 0.2 V, 2.3 Cb). This effect occurs in the range of rupture times that yield the minimum ductility (less than 10 percent) in the unnotch tests. Conversely, if the notched specimen fractures after 1850 hours at 1300° F, the notch strength is approximately 20 percent above the unnotch rupture strength. This rupture time corresponds to a ductility greater than 20 percent. A few tests were also made at 1300° F on another Ni-Cr-Co alloy (composition: 0.17 C, 17 Cr, 33 Ni, 20 Co, 3.8 Mo, 3.7 W, 1.7 Cb, 1.2 Mn, 2.1 Si) that indicate this material may become notch sensitive at rupture times over 1200 hours. No ductility values are reported for times over 400 hours. When tested at 1200° F up to 3000 hours, a Ni-Cr steel (composition: 0.15 C, 15 Cr, 31 Ni, 1.1 W, 0.86 Si, 1 Mo, 5 Ti) was insensitive to a variety of notches. Data for several other alloys are reported but the results are somewhat inconclusive because the notched bars were not tested in the ranges of low unnotch ductilities.

A number of tests (reference 3) have been made on full-scale turbine-blade root models of the fir-tree type to assist in realization of a rational design, which cannot be obtained from conventional rupture data. (The particular alloy considered was not mentioned.) At the low temperatures the blade-root teeth deform sufficiently to allow parting of the joint, whereas at high temperatures, much less deformation is evident and the failure occurs by cracking at the base of the teeth.

Effect of Chemical Composition and Heat Treatment on

Notch Stress-Rupture Characteristics of Low-Alloy Steels

Although no systematic investigations have been made, the data presented in the previous section plus a few other scattered results permit some tentative conclusions regarding the general effects of

alloy composition and heat treatment on the notch stress-rupture characteristics of low-alloy steels.

Apparently the Cr-Ni-Mo steels (references 7, 8, and 10) containing from 0.7 to 0.8 chromium, 0.9 to 1.5 nickel, and up to 1.0 molybdenum are extremely notch sensitive in stress-rupture tests at 932° F (500° C) either in the quenched-and-tempered or in the normalized condition. The elimination of nickel results in lower creep strengths but greatly reduces the notch sensitivity.

Further information regarding the effects of composition and heat treatment on the notch stress-rupture sensitivity is given in reference 4 for a large number of Cr-Mo steels containing various other alloying additions. Data are shown for only one fracture time, 10,000 hours, and one temperature, 932° F (500° C). In general, these data confirm the previous conclusion regarding the deleterious effect of nickel in the amounts mentioned. In addition, data are presented for Cr-Mo steels with 1 to 2.5 chromium and 0.3 to 1.3 molybdenum, plus various small amounts of nickel, silicon, vanadium, and tungsten. These steels were quenched from 1742° F (950° C), tempered at 1112° F (600° C) to 1292° F (700° C), and air cooled. The presence of up to 0.2 nickel did not result in notch sensitivity for compositions containing 0.1 to 0.2 vanadium. The addition of 0.8 to 1.0 silicon to steels of this type appears to improve the notch properties considerably.

The effect of annealing and sphereodizing on the notch and unnotch rupture strength is shown in references 8 and 10. The notch rupture strength is shown in figure 5 for an annealed Cr-Ni-Mo steel. When these data are compared with those for the same steel in the quenched-and-tempered condition, the annealed structure exhibits a considerably lower notch rupture strength at short times to rupture. The notch strength of the annealed condition, however, changes much less with increasing rupture time and is approximately 50 percent higher than that of the quenched-and-tempered steel at 500 hours.

The corresponding ductilities for the annealed steel are not reported; however, it would seem reasonable to assume that the ductility of the annealed structure would not drop to extremely low values in the range of rupture times investigated and therefore the observed notch strength trend would be expected.

The Cr-Ni-Mo steel represented in figure 6 was also investigated in the sphereodized condition (fig. 8) produced by tempering an oil-quenched specimen for 500 hours at 1256° F (680° C). The elongation of this structure is much higher than that of the quenched-and-tempered alloy (compare figs. 6 and 8) and rises with increasing time to rupture.

As might be expected, the notch rupture strength of the sphereodized steel is consistently higher than the unnotch strength for all rupture times investigated.

Both the quenched-and-tempered and the normalized-and-stress-relieved structures of Cr-Mo-Ni steel are notch sensitive. From the data available it is impossible to distinguish between these types of heat treatment regarding their effect on the notch sensitivity. For the previously mentioned group of Cr-Mo steels containing small quantities of nickel, vanadium, silicon, and tungsten (reference 4), the notch sensitivity is more pronounced if the quenching temperature is increased to 1868° F (1020° C). Also, Cr-Mo steels of this group containing additions of 0.7 vanadium and from 0.35 to 0.50 tungsten are notch sensitive if quenched from temperatures near 1900° F. In general, heat treatments designed to yield high creep strengths increase the notch sensitivity.

Mechanism of Stress-Rupture Embrittlement and

Notch Sensitivity in Low-Alloy Steels

An attempt to arrive at a mechanism of the severe stress-rupture embrittlement and notch sensitivity in the low-alloy steels would appear profitable because alloys of this type may be considered in certain cases as substitutes for some of the present-day highly strategic gas-turbine materials.

Examination of the data revealed several important phenomena which may clarify this mechanism:

(1) The unnotch ductility and the notch strength pass through a minimum at long times to rupture (see figs. 3 and 6).

(2) Annealed and sphereodized steels are not notch sensitive (see figs. 5 and 8).

(3) The influence on the room-temperature impact strength of heating at 932° F (500° C) for various times up to 9000 hours is given in reference 7 for several low-alloy steels. Brittle Cr-Mo-Ni steels of the type shown in figure 6 exhibit a distinct minimum in impact strength at 5000 hours. In contrast, the impact properties of a Cr-Mo-V steel, ductile in stress-rupture tests, remain practically constant with increase in the heating time.

(4) The retained impact strength at room temperature of low-alloy steel specimens held at a constant load at 932° F (500° C) for various

lengths of time (reference 7) reveal a progressively developing loss of impact strength with increasing time under load. This damage is most pronounced for the brittle Cr-Ni-Mo steels but can be partly recovered by a reheat treatment of the creep specimens.

These phenomena point to time-dependent and reversible structural changes as being primarily responsible for the stress-rupture embrittlement and consequent notch sensitivity in low-alloy steels. Such a change could be a precipitation reaction. It is a well-known fact that most steels are subject to precipitation effects and that these effects can influence the mechanical properties.

In order to study the problem with regard to a precipitation reaction, the relative effects of both time and temperature on the development of notch rupture sensitivity must be known. Data which would reveal this information are very meager; however, notch and unnotch stress-rupture tests are reported (reference 7) for a Cr-Ni-Mo steel at several temperatures. Figure 9 shows that at 572° F (300° C) the notch rupture strength is higher than the unnotch strength over the entire time range investigated. With an increase in testing temperature above 572° F (300° C) the strength of the notched bar falls below that of the unnotched specimen. The onset of this notch sensitivity in terms of rupture time passes through a minimum between 752° F (400° C) and 1112° F (600° C). A maximum in the difference between the notch and unnotch strength also occurs in this temperature range.

In order to represent the effects of time and temperature on the notch sensitivity more clearly, figure 10 has been constructed showing the dependence of the notch rupture-strength ratio (ratio of the strength of the notched bar to that of the unnotched bar) on the testing time and temperature.

An attempt has been made in figure 11 to show qualitatively that the conventional conceptions regarding the effects of precipitations can explain the results of figure 10.

From the known effects of precipitation on the room-temperature mechanical properties, a hypothetical set of curves was drawn (fig. 11(a)). These curves qualitatively illustrate the anticipated effects of temperature and time on the unnotch rupture ductility when precipitation is the controlling phenomenon. In figure 11(a) the rupture ductility has been assumed to increase continuously with temperature at times which are insufficient to develop the precipitation reaction. With increasing time to rupture, a minimum in the curve of ductility against temperature develops, which becomes more pronounced (up to a maximum effect) and shifts to lower temperatures

the longer the time to rupture. The next relation that is desired is
variation of the notch rupture-strength ratio with time and temperature.
In order to determine this variation, a relation must be assumed
between unnotch ductility and notch rupture-strength ratio. The notch
rupture-strength ratio is assumed constant at 1.1 for ductilities of
over 10 percent and for lower ductilities to closely parallel the trend
of the ductility (fig. 11(b)). These assumptions are based on the
evidence previously presented for the influence of unnotch ductility
on the notch rupture strength. Replotting the curves in figure 11(b)
as a function of time for the temperatures T_1, T_2, T_3, and T_4 then
yields the notch rupture-strength ratio as a function of time to
rupture (fig. 11(c)). This general picture agrees with the results
previously presented in figure 10.

If a precipitation reaction is responsible for the stress-rupture
embrittlement of low-alloy steels, the exact nature of the precipitate
cannot be stated on the basis of the evidence published. Loss of
impact energy for specimens heated various lengths of time between
900° and 1000° F has already been associated with the type of precipi-
tation thought to cause temper brittleness. However, it must be
remembered that these steels contain molybdenum well in excess of the
amount believed to be sufficient to eliminate temper brittleness in
the ordinary sense (reference 12).

Low-alloy steels are not the only metals exhibiting stress-rupture
embrittlement and recovery. Unpublished results obtained by Freeman
and White at the University of Michigan for some recently developed
high-temperature alloys show that several minimums may occur in the
elongation values when plotted as a function of time to rupture.

Comparison of Influence of Ductility and Notch Geometry

in Notch Tensile Tests and in Notch Rupture Tests

From the data presented, it is evident that the notch rupture
strength may be either greater or smaller than the rupture strength
for the unnotched bar. These general effects may be compared with and
partly explained by known facts regarding the influence of ductility
on the notch tensile strength at room temperature.

Previous investigations regarding the effects of notches on the
tensile strength at room temperature (references 2 and 13 to 15)
indicate the introduction of notch results in the superposition of two
different phenomena: (1) strengthening due to the lateral restraint
to plastic flow and (2) weakening due to nonuniformity of the stresses
and strains in the notched cross section. The relative magnitude of

these two effects depends on metal properties that are not yet clearly defined but are definitely related to the ductility of the metal under the conditions of notching. If this ductility is sufficient, plastic flow will eliminate the initial stress concentration, thereby increasing the uniformity of stresses. With regard to the effects of these phenomena on the tensile strength, metals may be divided into two classes: (1) metals that exhibit only the strengthening effect however severe are the notches, and (2) "notch-brittle" metals for which the weakening effect predominates under severe conditions of notching.

Although the notch stress-rupture data presented previously are quite meager when compared with that obtained for notch tensile tests, it appears that these two classes of strength behavior are also observed. For notch tensile tests, the weakening effect of a sharp notch is known to be related to the ductility of the metal under the conditions of notching but is not related to the high ductilities (greater than 30 percent) of the unnotched bars. This has been demonstrated clearly for a series of low-alloy steels (reference 2) heat-treated to various tensile strengths and tested with the sharpest possible notch. For these steels (fig. 12), a universal relation exists between the notch strength ratio and the notch ductility. The notch strength ratio is dependent on the notch ductility only if this ductility is less than approximately 4 percent. For notch ductilities less than this value, changes in the notch ductility would be reflected by corresponding changes in the notch strength. However, it would seem reasonable to assume that if a material is sufficiently brittle in an unnotch test the notch strength should depend on the unnotch ductility as well as on the notch ductility. Thus, the corresponding changes in unnotch rupture ductility and notch rupture strength with time (figs. 5 and 6) might be expected and explained also on the basis of a retained stress concentration.

The only series of rupture tests which clearly reveal the influence of notch geometry are for a 94 Sn-6 Cd alloy (reference 16). In figure 13 these data are replotted to show the effects of notch sharpness on the notch rupture strength for various times to rupture. Data for the various notch depths have been incorporated into the representation; however, no effect of this variable is noted except at the longer times to rupture.

In figure 14 the variations in the notch rupture-strength ratio for the 94 Sn-6 Cd alloy replotted from figure 13 are compared with those for room-temperature notch tensile tests on a SAE 3140 steel (reference 14) having approximately the same notch depth. The curve in figure 14(a) for the steel with a strength of 190,000 pounds per square inch is typical for a "notch-ductile metal", which exhibits only the strengthening effect. The curve for the 100-hour notch

rupture-strength ratio follows the same trend. In both cases the
initial strengthening is indicated by an increase in the notch strength
ratio with increasing notch sharpness in the range of relatively mild
notches (up to a notch sharpness of approximately 6). This increase
is explained by the increase in triaxiality (reference 13), which
raises the flow stress and consequently the maximum load. For the
higher notch sharpnesses, the notch strength ratio decreases slightly.
A decrease in the strengthening effect (a smaller rate of increase of
the notch strength ratio) at the higher notch sharpness might be
expected because the rate of increase of triaxiality becomes less with
increasing notch sharpness (reference 13). At high sharpness values
the slight decrease in the notch strength ratio with an increase in
notch sharpness is not readily explained but may be related to the
strain concentration, which increases rapidly in the range of severe
notches (reference 15); this nonuniformity of strain may affect the
shape of the average stress-strain curve in such a manner as to cause
instability to occur at lower loads.

The case of a metal that is weakened by notching is illustrated
in figure 13(b) for 1000-hour notch-rupture tests on the Sn-Cd alloy
and for notch tensile tests on the SAE 3140 steel heat-treated to
a strength level of 240,000 pounds per square inch. At this high
strength level, the SAE 3140 steel is notch brittle. The weakening
is exhibited only if the notch sharpness exceeds a certain value.
Below this value, the strengthening effect predominates and the initial
increase in the notch strength ratio can be again explained on the
basis of the variation in the triaxiality. In the range of higher notch
sharpnesses, however, the notch strength ratio decreases rapidly to
values below unity at a rate that depends on the ductility under the
conditions of notching. This weakening effect can be explained by the
following considerations: (1) In this region, the triaxiality
(strengthening), as was previously explained, is increasing only
slightly with increasing notch sharpness and consequently the average
stress is little influenced by this factor. (2) The ductility of the
metal is not sufficient to eliminate completely the initial stress
concentration. This retained stress concentration is primarily depen-
dent on the sharpness and increases rapidly at high notch-sharpness
values. The notch strength is then no longer related to an instability
but decreases with the average fracture stress, which, in turn, depends
inversely on the stress concentration.

Problems Requiring Further Clarification

For the types of heat-resisting low-alloy steel discussed pre-
viously, the significance of unnotch rupture ductility with regard to
notch sensitivity appears quite definite when below 2 or 3 percent.

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In general, it would seem probable that low-alloy steels should be weakened by stress raisers in long-time high-temperature loading if their unnotch ductility falls below approximately 5 percent. However, an extension of this conclusion to austenitic alloys and medium-alloy steels must await future investigation.

A second problem is related to significance of unnotch ductility above values of approximately 5 percent. It is impossible to state definitely that an alloy exhibiting ductilities above this value will not be notch sensitive. This statement can be based on the notch brittleness observed in tensile tests of presumably highly ductile low-alloy steels (reference 2). It is further supported by some stress-rupture results presented in reference 17 for a quenched-and-tempered Cr-Ni-Mo-V steel. It is shown that at 700° F, although the unnotch rupture ductility remains always above 10 percent, thread failures were encountered.

A definite knowledge of the effects of notch geometry on the notch rupture strength of various types of alloy steel should be distinctly helpful to the designer concerned with fastening problems at elevated temperatures. Thus, it should be possible on the basis of notch rupture tests to state design limits for notches of various sharpnesses.

Finally, the mechanism of stress-rupture embrittlement as influenced by composition and heat treatment requires further clarification. Investigations are needed to establish development of embrittlement as a function of time and temperature and to search for structural changes which may accompany such embrittlement.

CONCLUDING REMARKS

A review of the published data on notch rupture investigations has revealed several significant facts regarding the general influence of notching on the elevated-temperature long-time properties for the alloys considered:

1. A notch sensitivity in stress-rupture tests has been observed for several alloys including a group of heat-resisting steels.

2. This sensitivity appears to be related to the ductility of the material under the conditions of the stress-rupture test. Highly ductile metals were not notch sensitive, whereas a progressively increasing notch sensitivity developed if the unnotch rupture ductility fell below approximately 5 percent.

3. For the heat-resisting low-alloy steels, addition of nickel in amounts greater than approximately 0.7 percent appears to increase the

notch rupture sensitivity greatly. The quenched-and-tempered and the normalized-and-stress-relieved structures of these alloys appear to be more notch sensitive than the annealed or sphereodized structures.

4. The notch sensitivity in Cr-Ni-Mo low-alloy steels appears to be associated with a time-and-temperature-dependent precipitation phenomenon.

5. The general influence of one of the important geometrical variables, the notch sharpness, has been shown to be the same in rupture tests as previously was observed in notch tensile tests at room temperature.

6. Without a more definite knowledge of the structural factors leading to embrittlement, it would seem somewhat premature to generalize these conclusions and extend them to classses of materials not yet investigated.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, March 27, 1951.

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R, radius at notch bottom
d_0, diameter at minimum section
d_1, diameter of cylindrical section
θ, flank angle
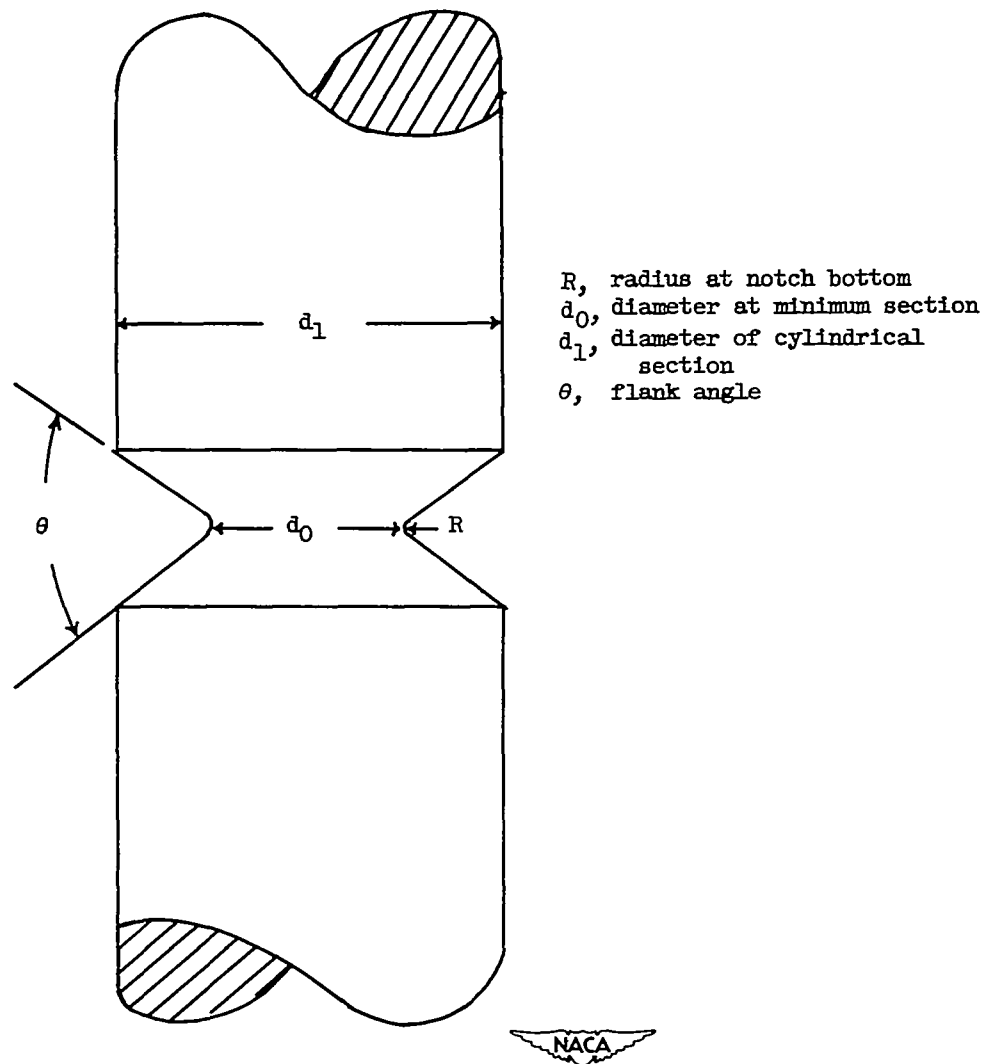
Figure 1. - Dimensions necessary to define notch geometry for a cylindrical bar.
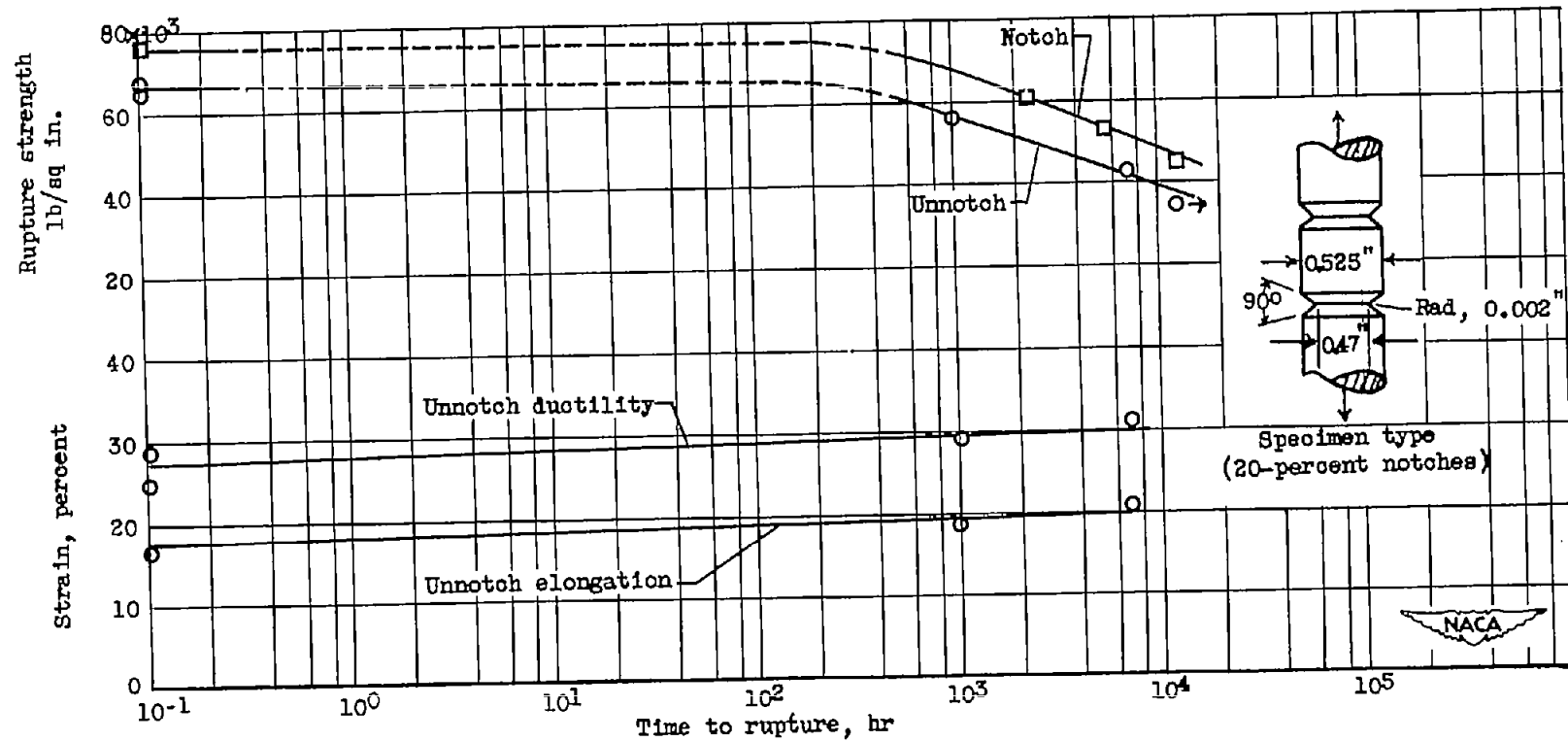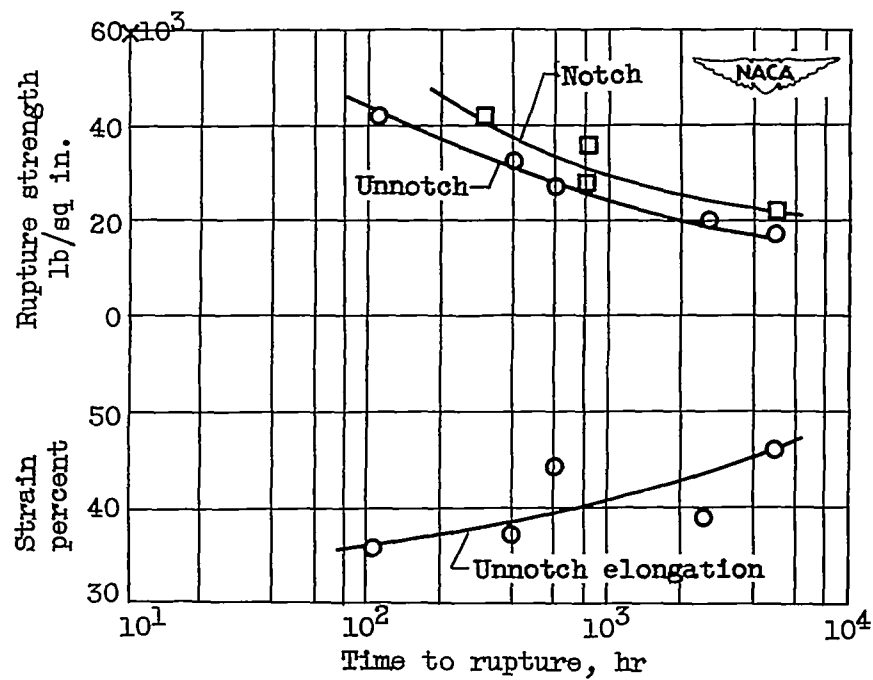
Figure 2. - Stress rupture characteristics at 932° F (500° C) for notched and unnotched specimens of chromium steel (reference 7). Composition: < 0.1 C, 20 Cr, 1.0 Mo, and 0.35 Si; heat treatment: 1382° F (750° C) to 1472° F (800° C), air cooled.
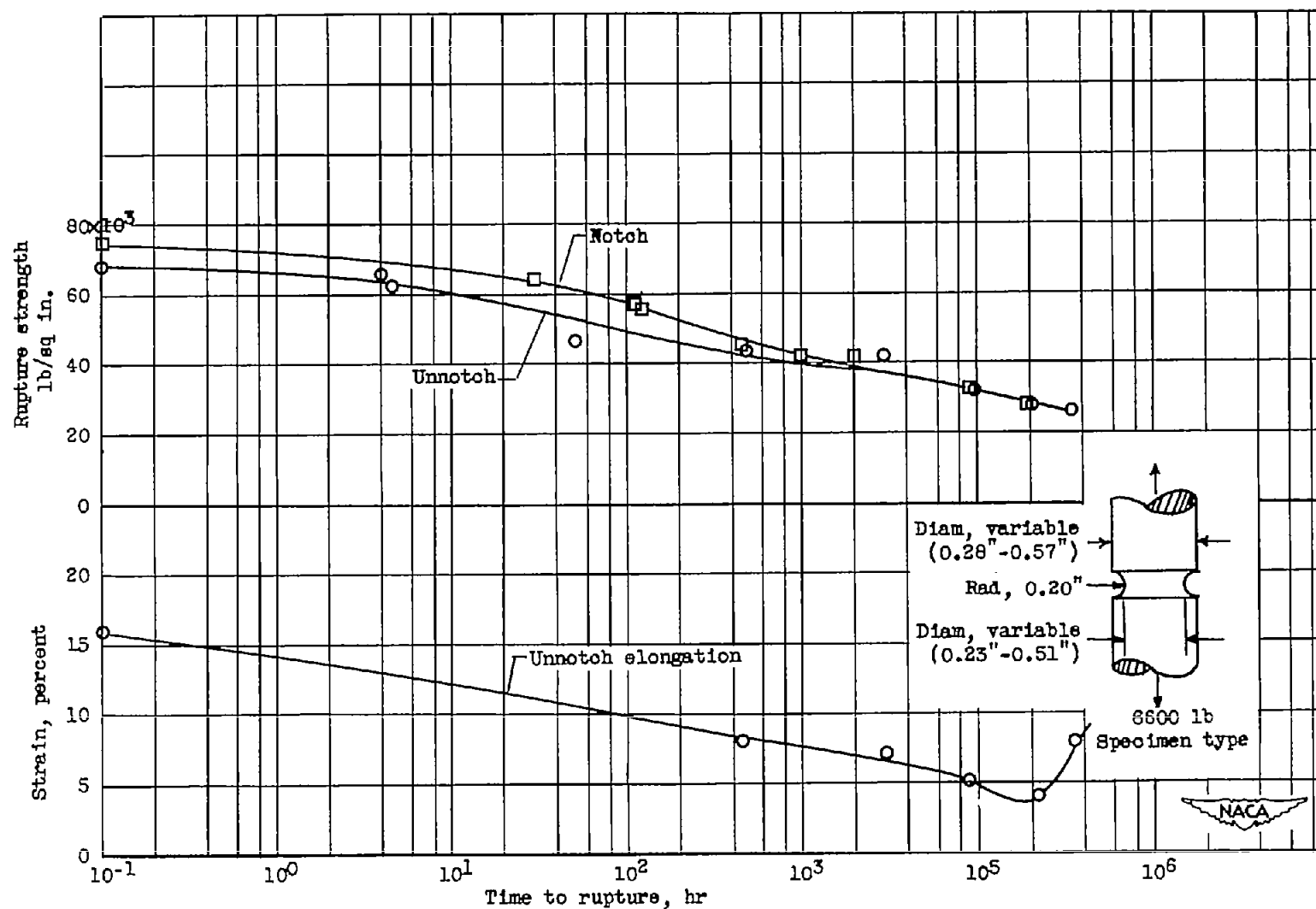
Figure 3. - Stress-rupture characteristics at 932° F (500° C) for notched and unnotched specimens of Cr-Mo steel (references 8 and 9). Composition: 0.19 C, 0.7 Cr, 0.4 Mo, 0.32 Si; heat treatment: normalized at 1652° F (900° C) and stress relieved at 1166° F (630° C).
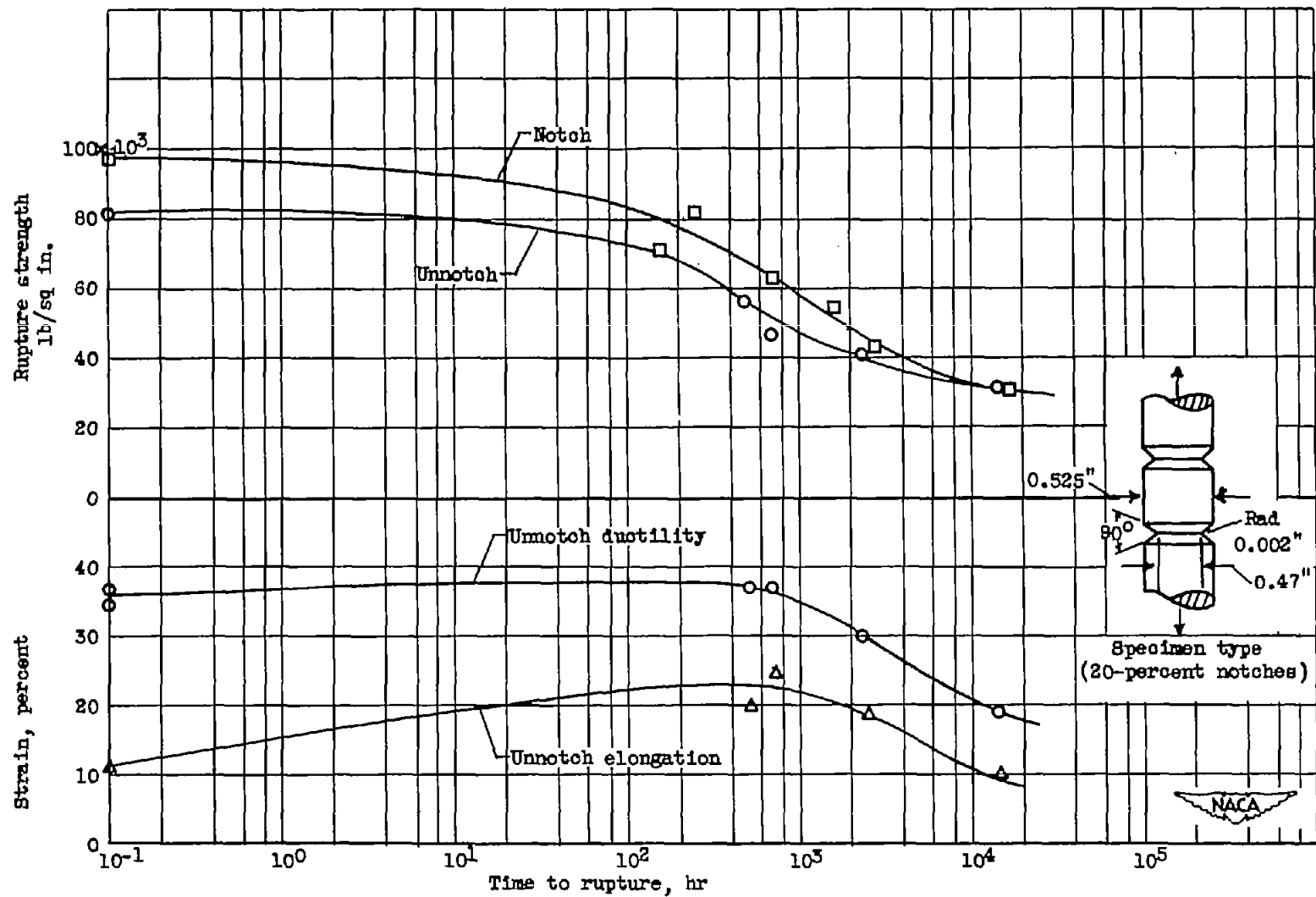
Figure 4. - Stress-rupture characteristics at 932° F (500° C) for notched and unnotched specimens of Cr-Mo steel (reference 7). Composition: 0.3 C, 1.6 Cr, 1.3 Mo, 0.27 Si, 0.1 V; heat treatment: normalized at 1742° F (950° C) and stress relieved at 1256° F (680° C).
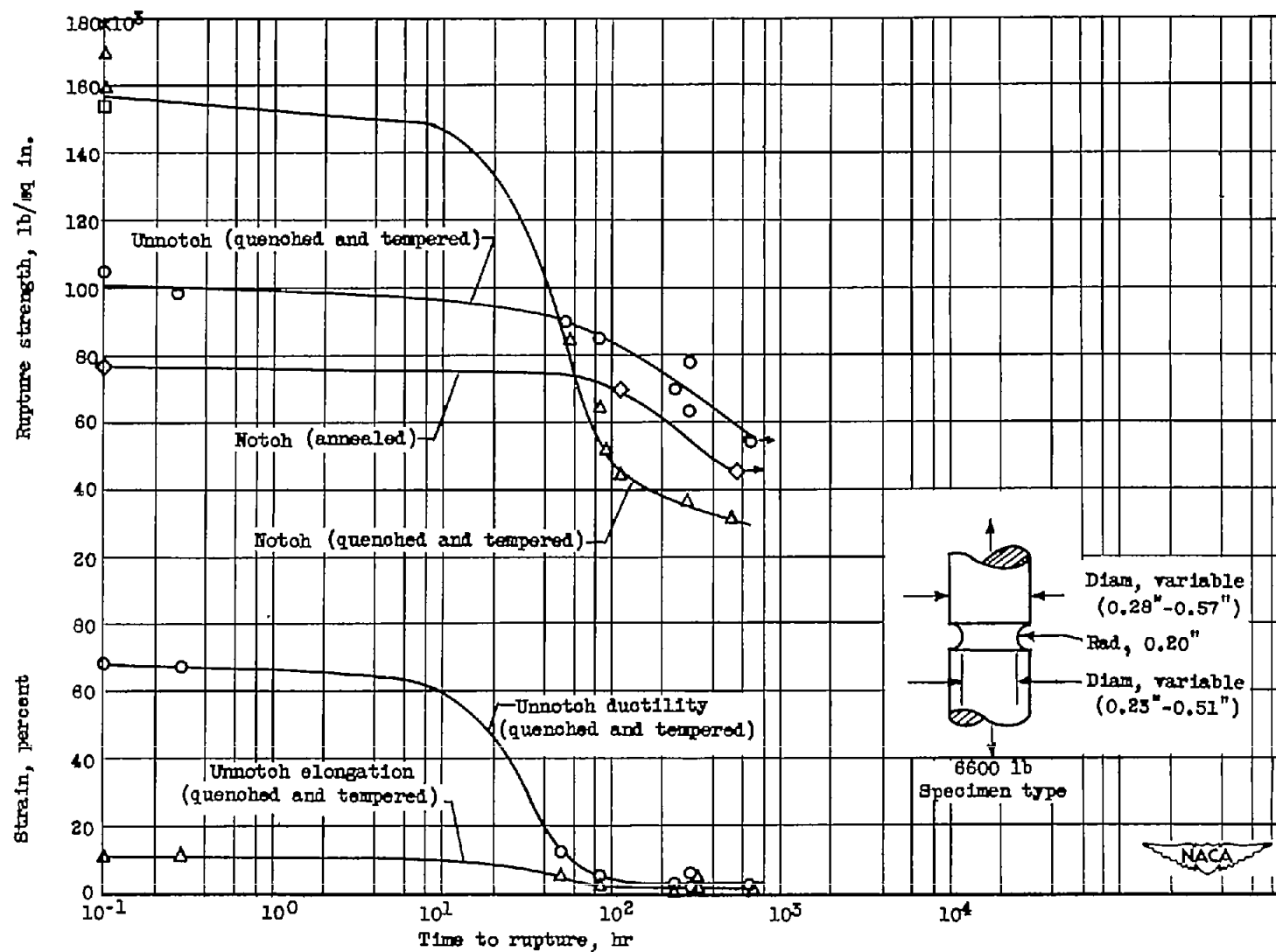
Figure 5. - Stress rupture characteristics at 932° F (500° C) for notched and unnotched specimens of Cr-Ni-Mo steel (reference 10). Composition: 0.12 C, 0.7 Cr, 1.6 Ni, 0.8 Mo.
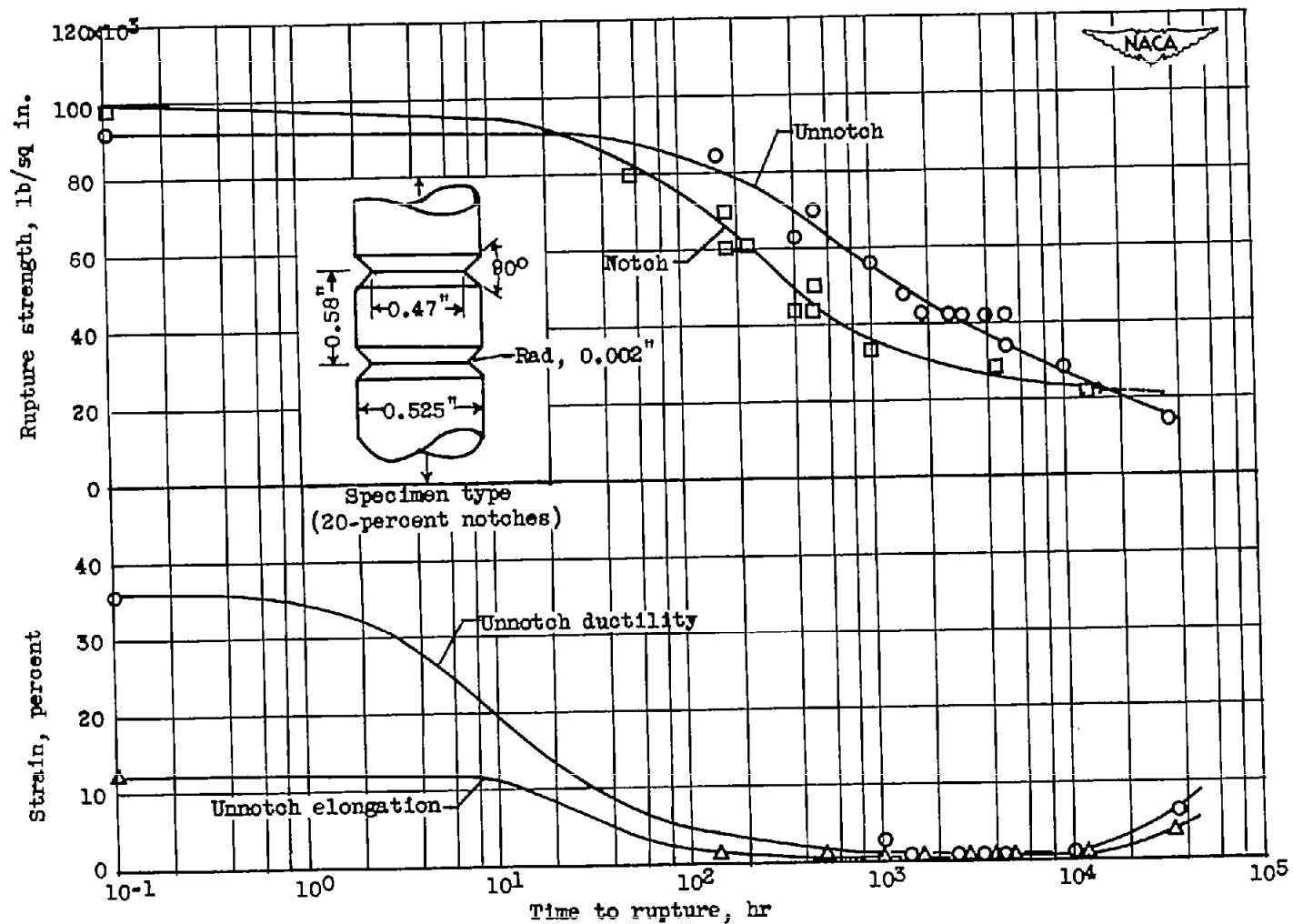
Figure 8. - Stress rupture characteristics at 932° F (500° C) for notched and unnotched specimens of Cr-Ni-Mo steel (references 7 and 8). Composition: 0.11 C, 0.7 Cr, 1.5 Ni, 0.88 Mo, 0.22 Si; heat treatment: 1598° F (870° C), oil quenched and 1112° F (600° C), air cooled.

(a) Tested at 110° F.

(b) Tested at room temperature.
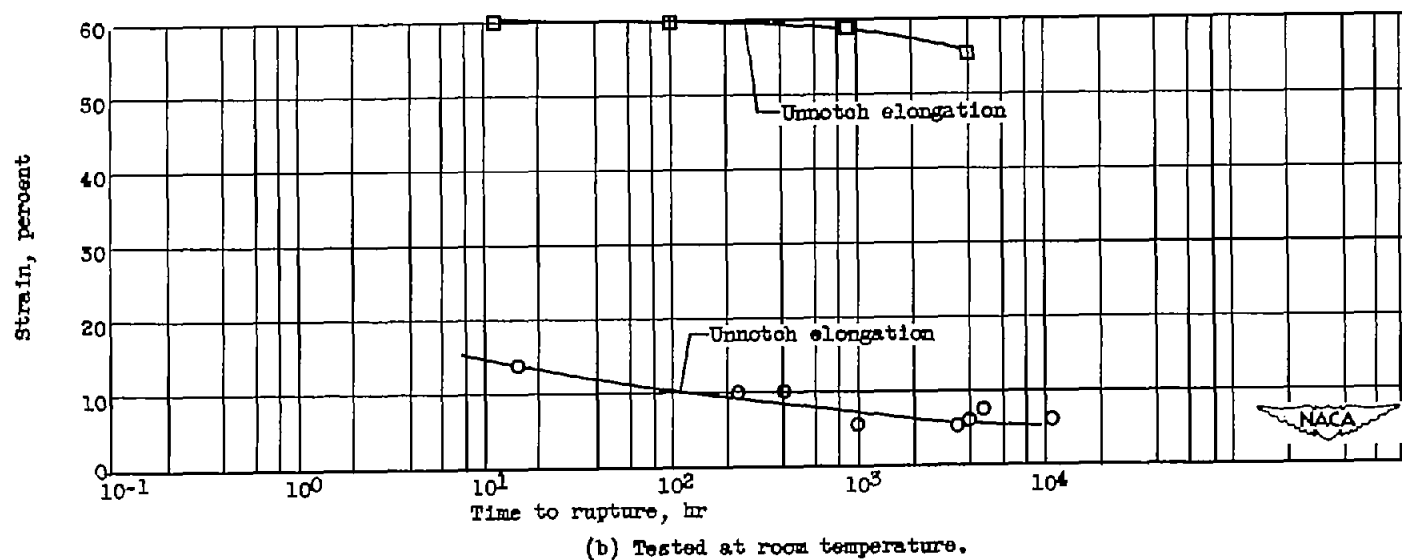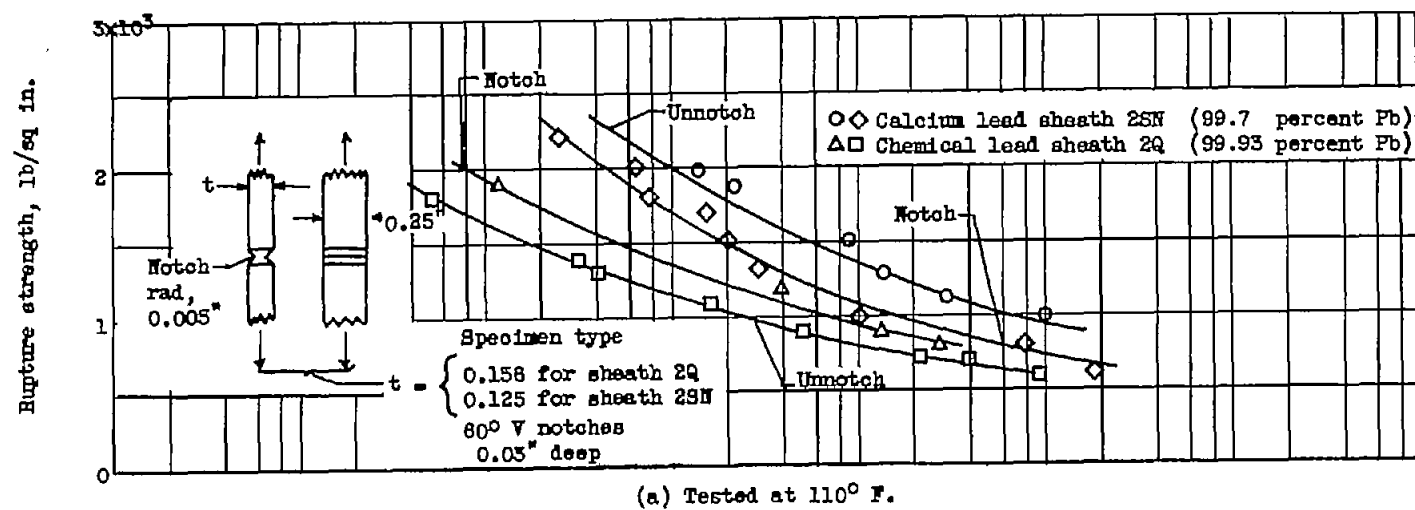
Figure 7. - Stress-rupture characteristics for unnotched and notched specimens of two commercial lead cable sheathing alloys (reference 11).

Figure 8. - Stress-rupture characteristics at 932° F
(500° C) for notched and unnotched specimens of
sphereodized Cr-Ni-Mo steel (reference 8). Com-
position: 0.11 C, 0.7 Cr, 1.5 Ni, 0.88 Mo, 0.22 Si;
heat treatment: 1598° F (870° C), oil quenched and
1256° F (680° C) for 500 hours.
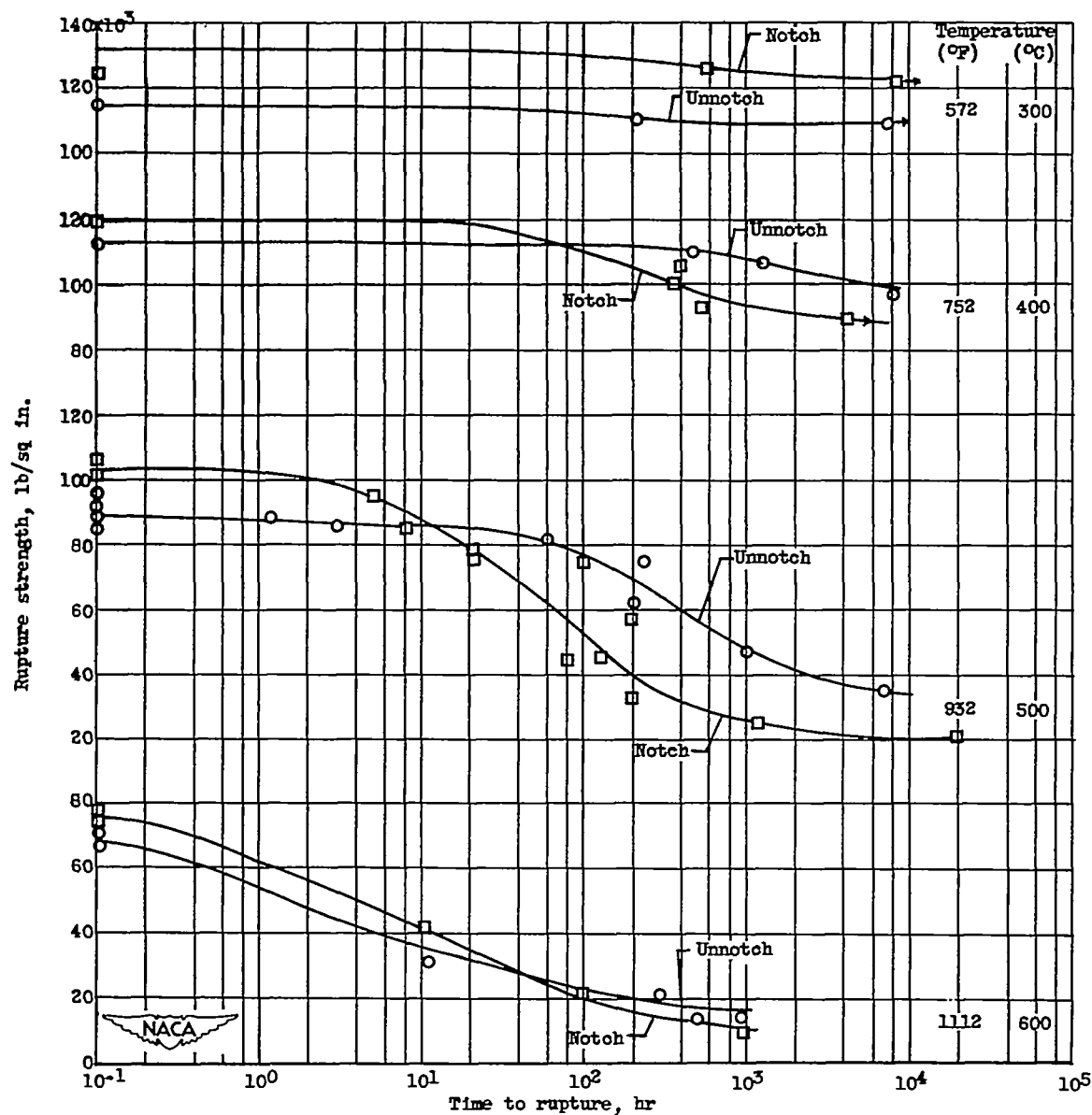
Figure 9. - Rupture strength for notched and unnotched specimens of Cr-Ni-Mo steel at various temperatures (reference 7). Composition: 0.2 C, 0.8 Cr, 0.9 Ni, 0.48 Si, 0.9 Mo; heat treatment: normalized at 1742° F (950° C) and stress relieved at 1148° F (620° C).
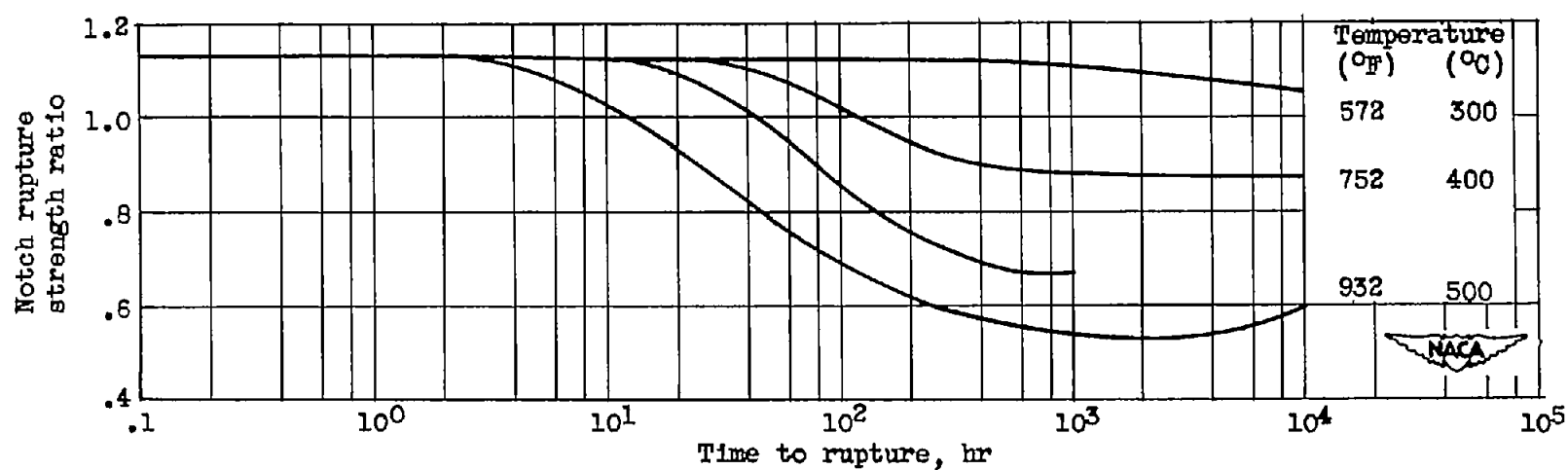
Figure 10. - Notch rupture-strength ratio for Cr-Ni-Mo steel at various temperatures (reference 7).
Composition: 0.2 C, 0.8 Cr, 0.9 Ni, 0.48 Si, 0.9 Mo; heat treatment: normalized at 1742° F
(950° C), stress relieved at 1148° F (620° C).
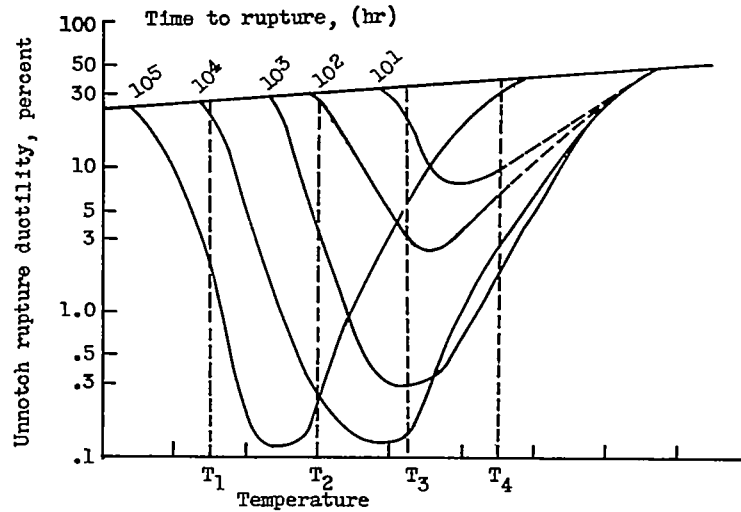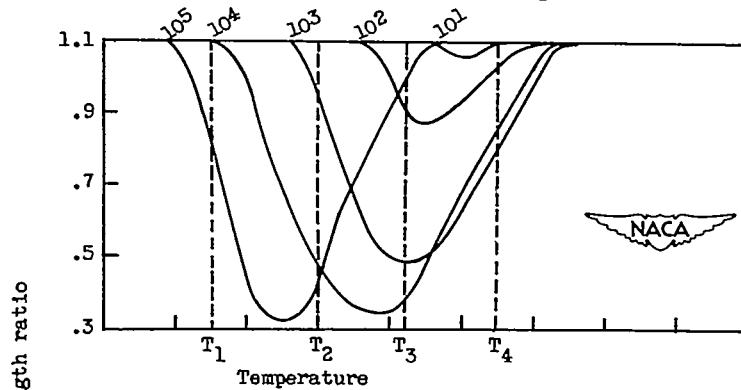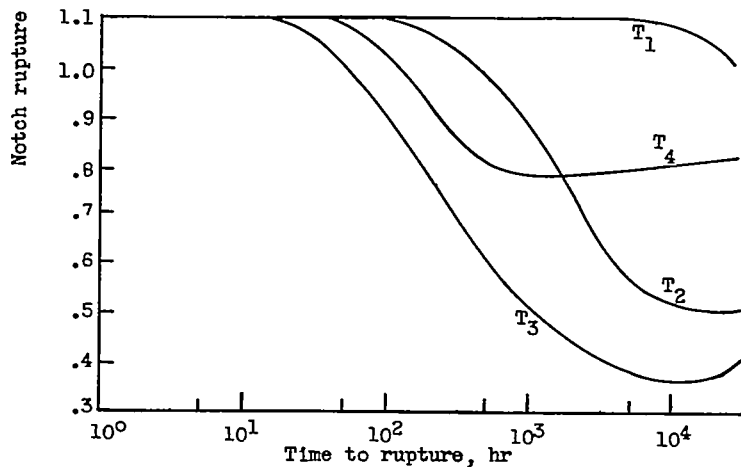
Figure 11. - Schematic derivation of time-temperature dependence of notch rupture-strength ratio from time-temperature dependence of unnotch rupture ductility.
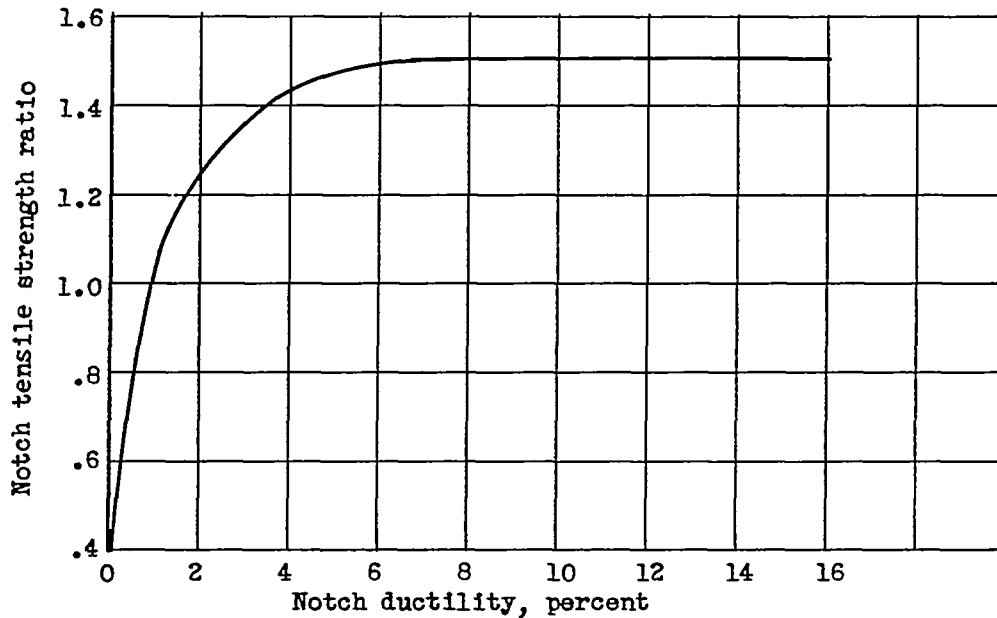
Figure 12. - Dependence of notch tensile strength ratio
on notch ductility for low-alloy steels SAE 2340, 5140,
and 1340 (reference 2). Heat treatment: quenched and
tempered to various strength levels between 190,000 and
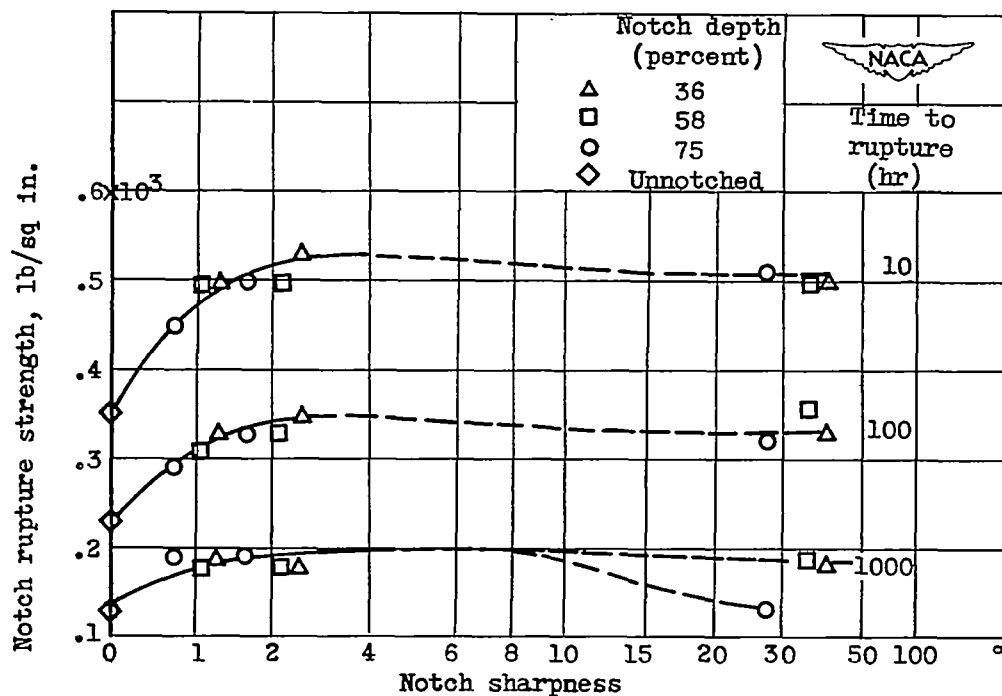320,000 pounds per square inch; 50 percent 60° V notches.
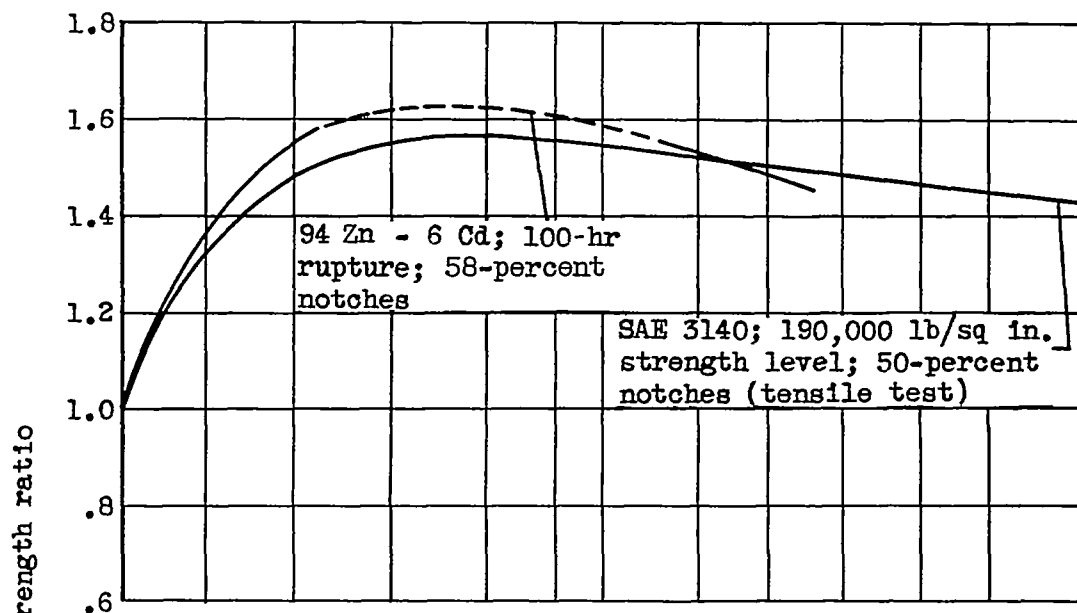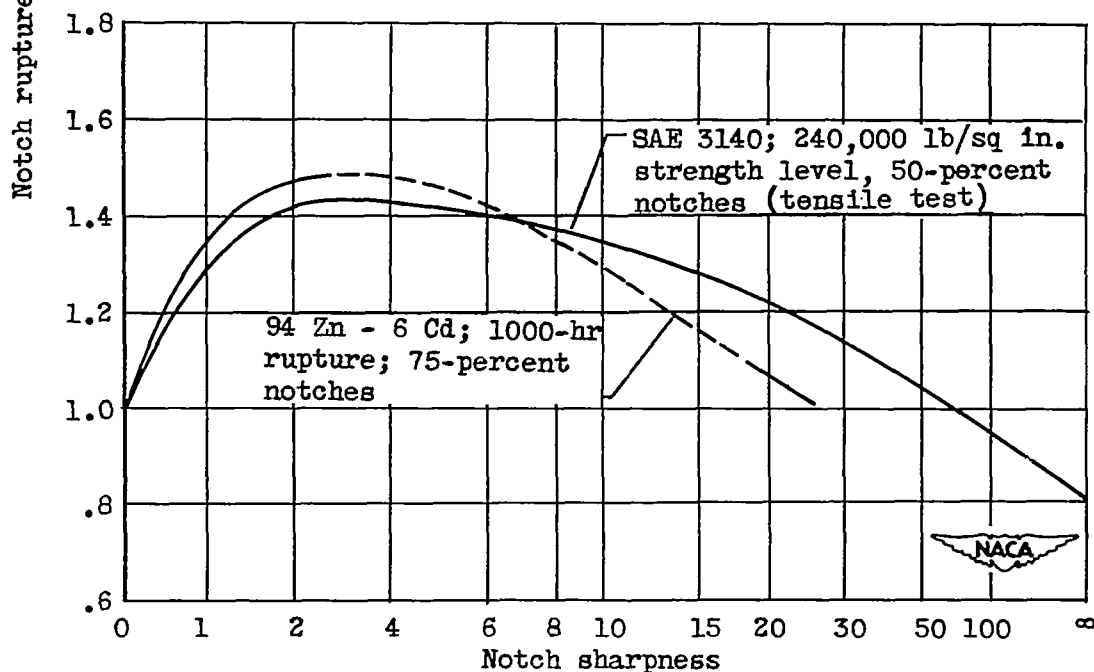
Figure 13. - Influence of notch sharpness (60° V notches) on strength
at three times to rupture for 94Sn-6Cd alloy (reference 16).

(a) Typical for notch ductile material.

(b) Typical for notch brittle material.

Figure 14. - Dependence of notch rupture-strength ratio on notch sharpness (60° V notches) for static tensile tests (reference 14) and for rupture tests (reference 16).